Interferometer Design for Synthesis Imaging

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Strategies for Imaging Complex Sources
Array Design for Synthesis Imaging
Beam Combination and Modulation for Synthesis Imaging
The Next Generation of for Synthesis Imaging Arrays

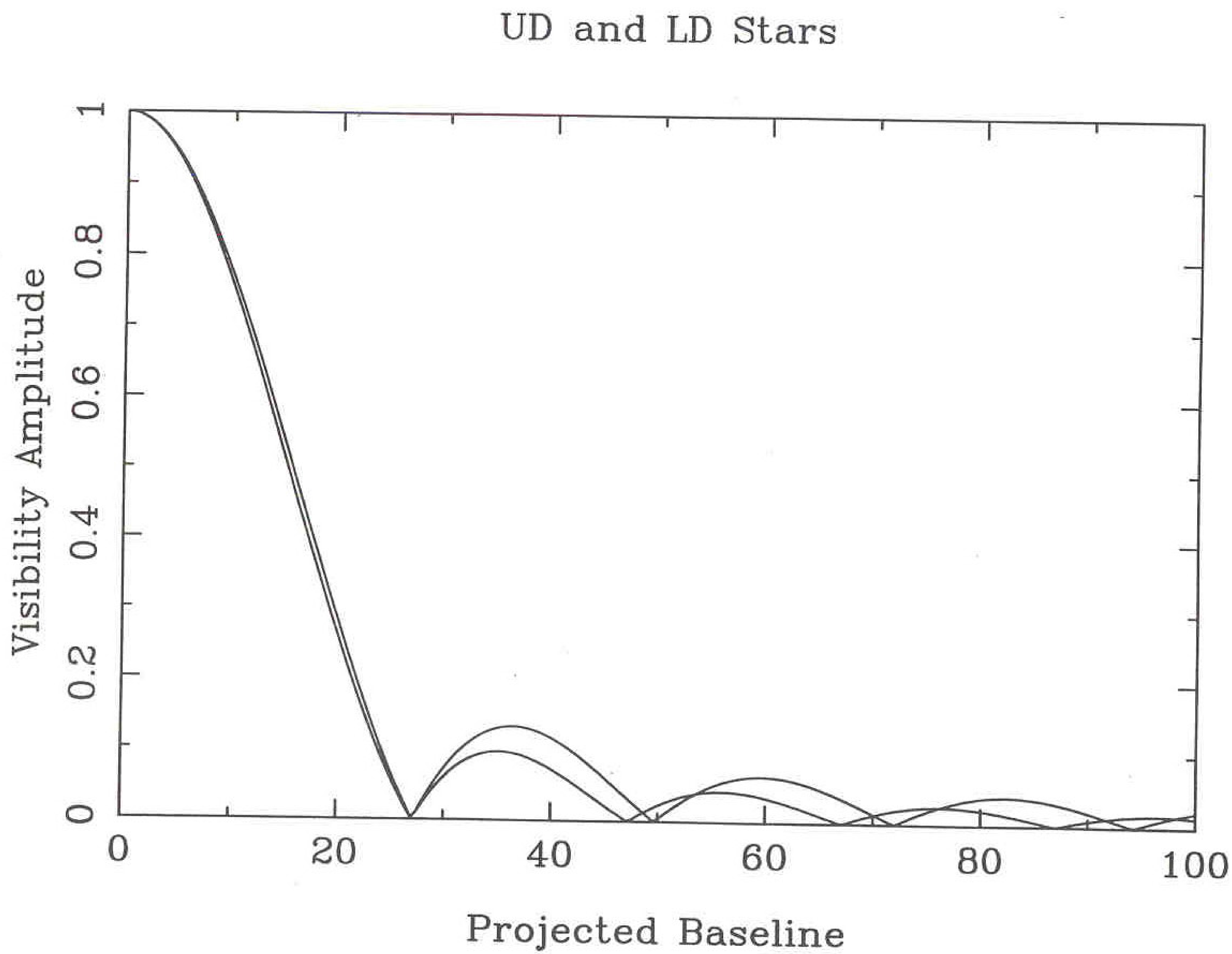
Strategies for Imaging

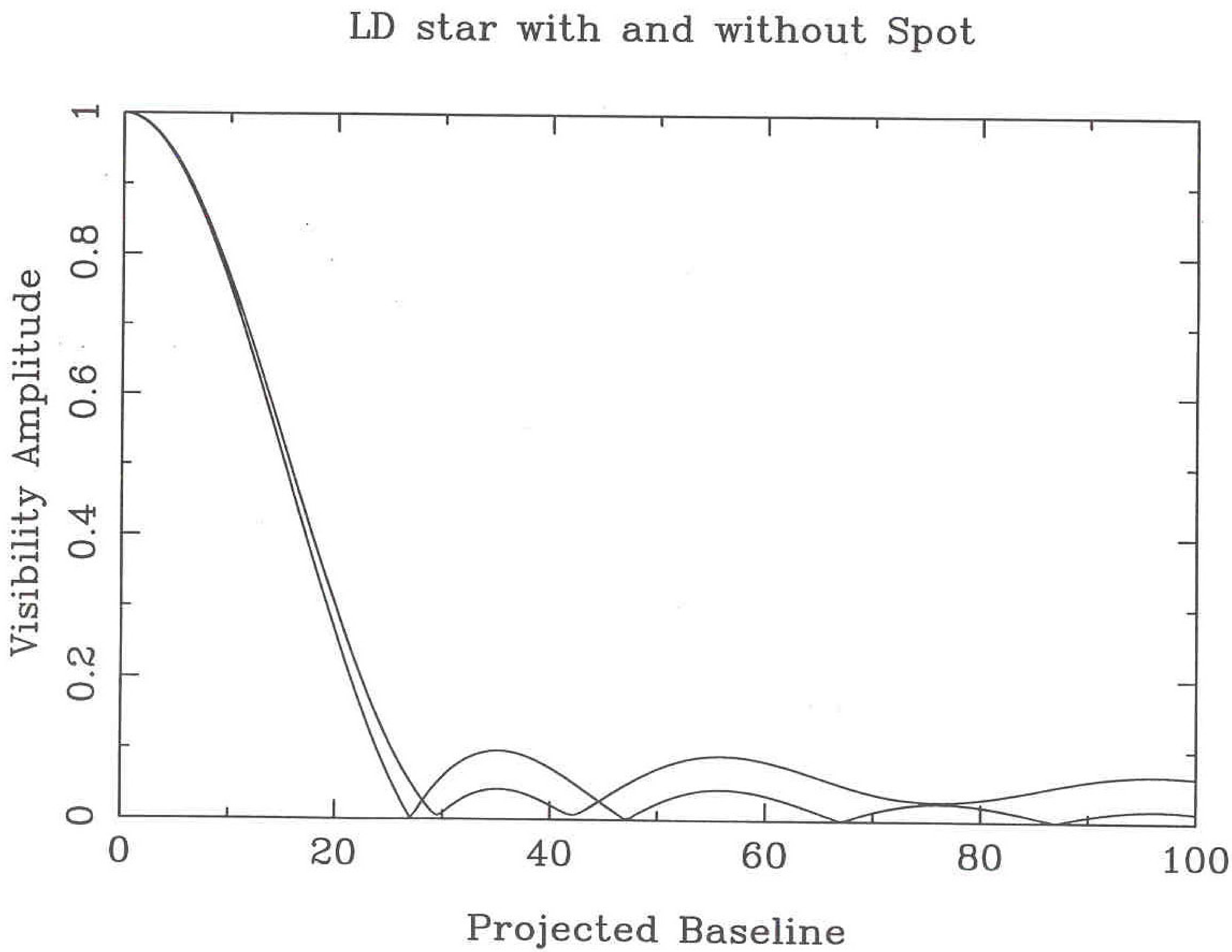
Example Visibility Functions

Statement of the problem

Implications for the Interferometer

- Fringe Detection
- Array Layout


UD and LD Stars
Visibility Amplitude
Projected Baseline
0
0.2
0.4
0.6
0.8
1
0
20
40
60
80
100



LD star with and without Spot
Visibility Amplitude
0
0.2
0.4
0.6
0.8
1
0
20
40
60
80
100
Projected Baseline

General Properties of Interesting Sources at Visible Wavelengths.

Most Power is at Low spatial frequencies.

Most Interest is at Higher spatial frequencies.

The baselines that contain interesting information also contain very low signal to noise.

But the atmosphere forces us to fringe track which implies we need a specified SNR in a specified integration time

The Hard Choice

Either

Record Useful Data

Or

Look at Interesting Sources

I know 5 Alternatives

Alternative 1: Integrate Forever

Some interferometers do not fringe track so why not integrate long enough to get a useful signal to noise ratio?

Fringe Amplitude Signal to Noise

$\sqrt{NV^2}$	High Signal
NV^2	Low Signal

But it is worse. Since the fringe position cannot be known in advance, we either

1. Use narrower bandpass and throw away more light

or

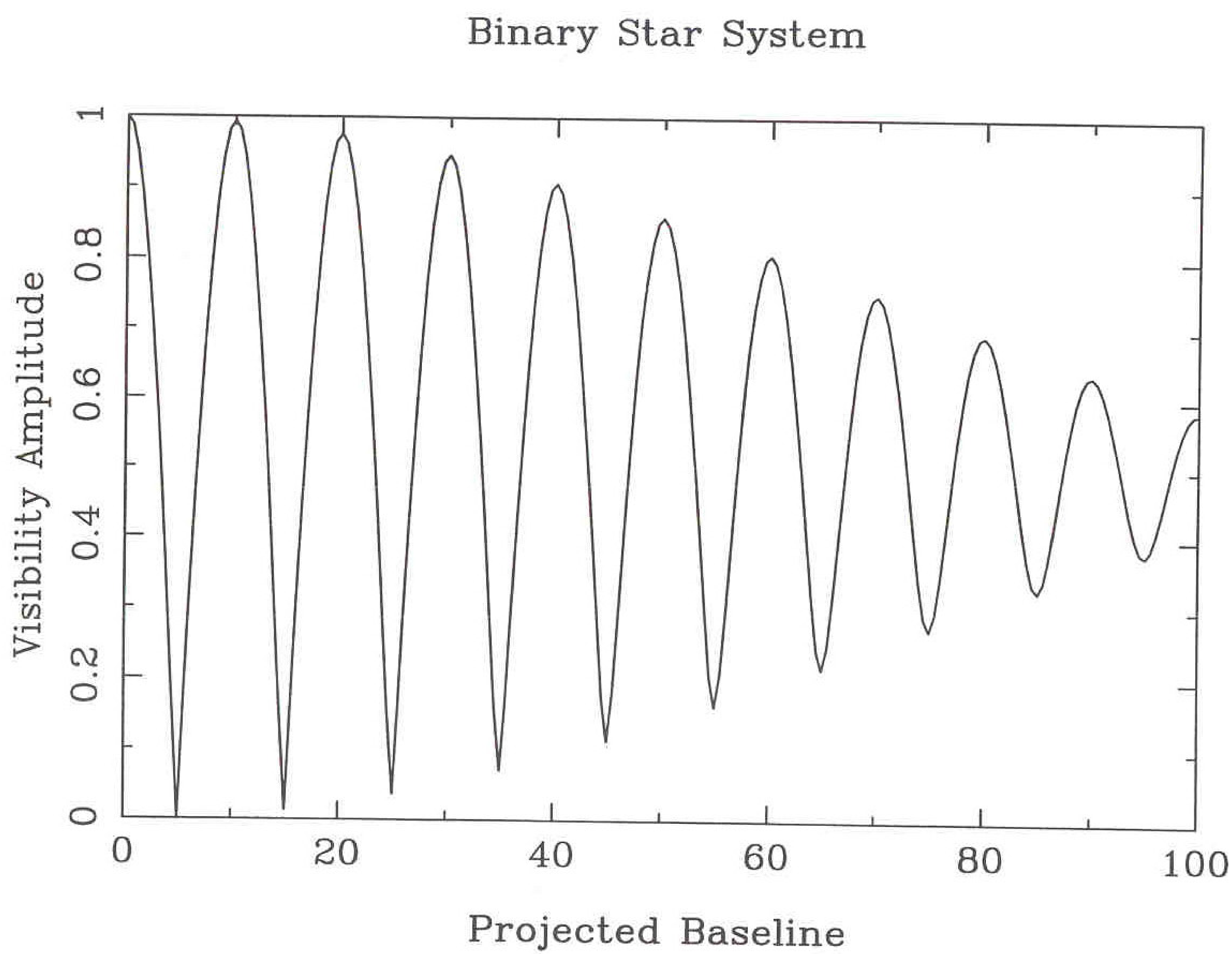
2 SCAN OVER LOTS OF DELAY AND ADD EXTRA NOISE

Alternative 2:

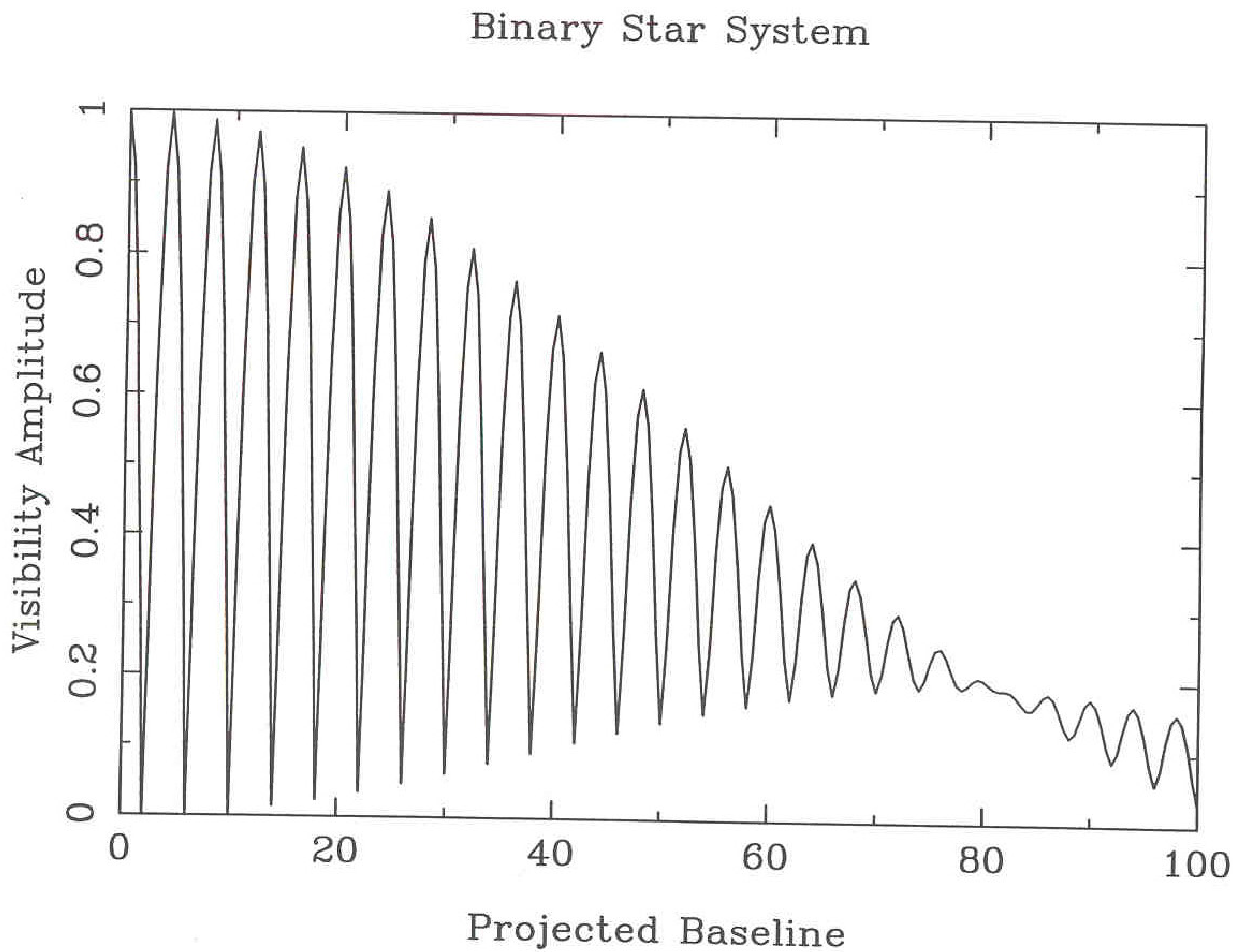
Observe Only Those Sources with High Visibility on Long Baselines

AND

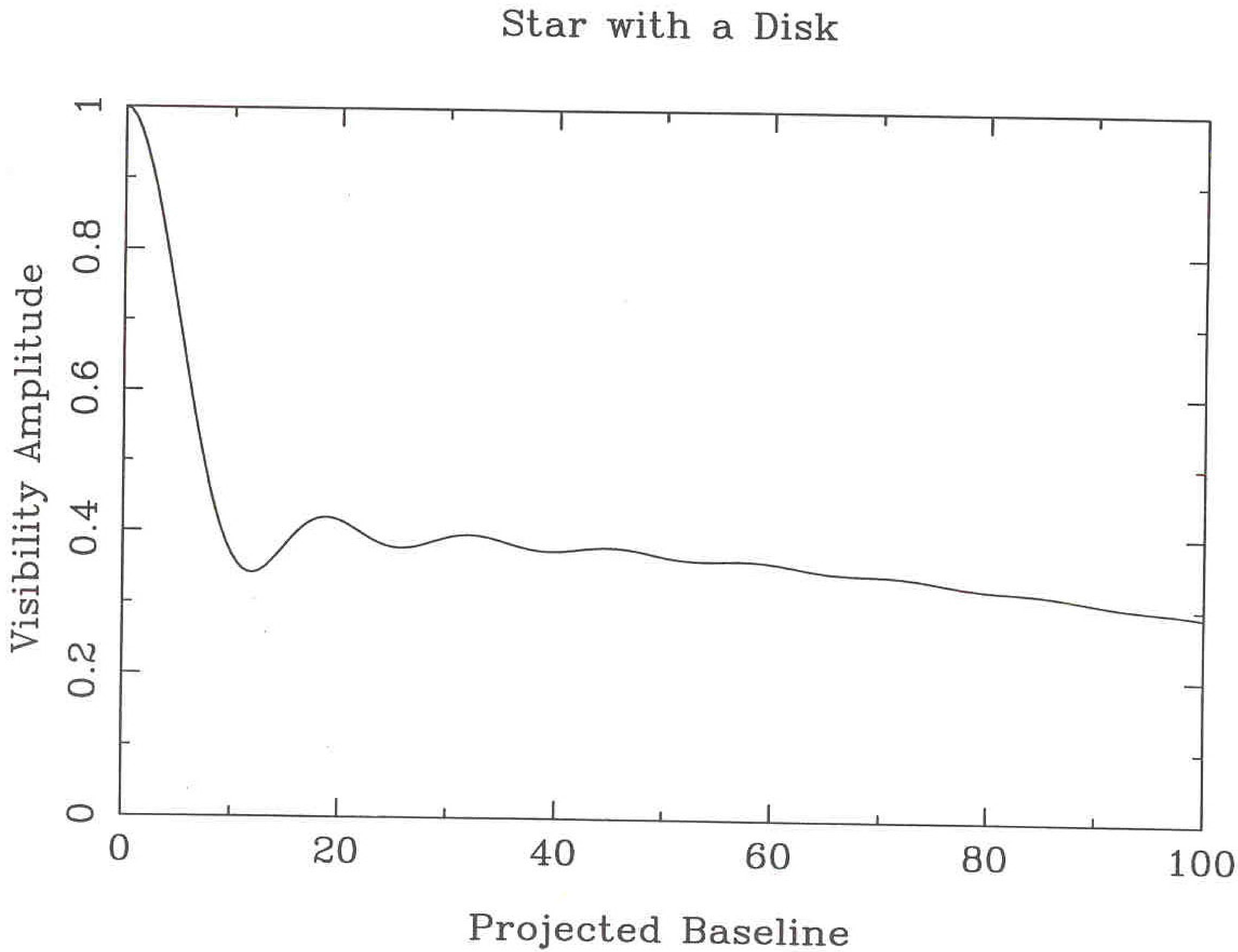
Assert with Great Confidence and Fanfare that These are Indeed Interesting Sources!



Binary Star System
Visibility Amplitude
Projected Baseline
0
0.2
0.4
0.6
0.8
1
0
20
40
60
80
100



Binary Star System
Visibility Amplitude
0
0.2
0.4
0.6
0.8
1
0
20
40
60
80
100
Projected Baseline


Star with a Disk
Visibility Amplitude
0
0.2
0.4
0.6
0.8
1
0
20
40
60
80
100
Projected Baseline

Alternative 3: Wavelength Bootstraping

Track the Fringe at a Long Wavelength while Observing at a Short Wavelength.

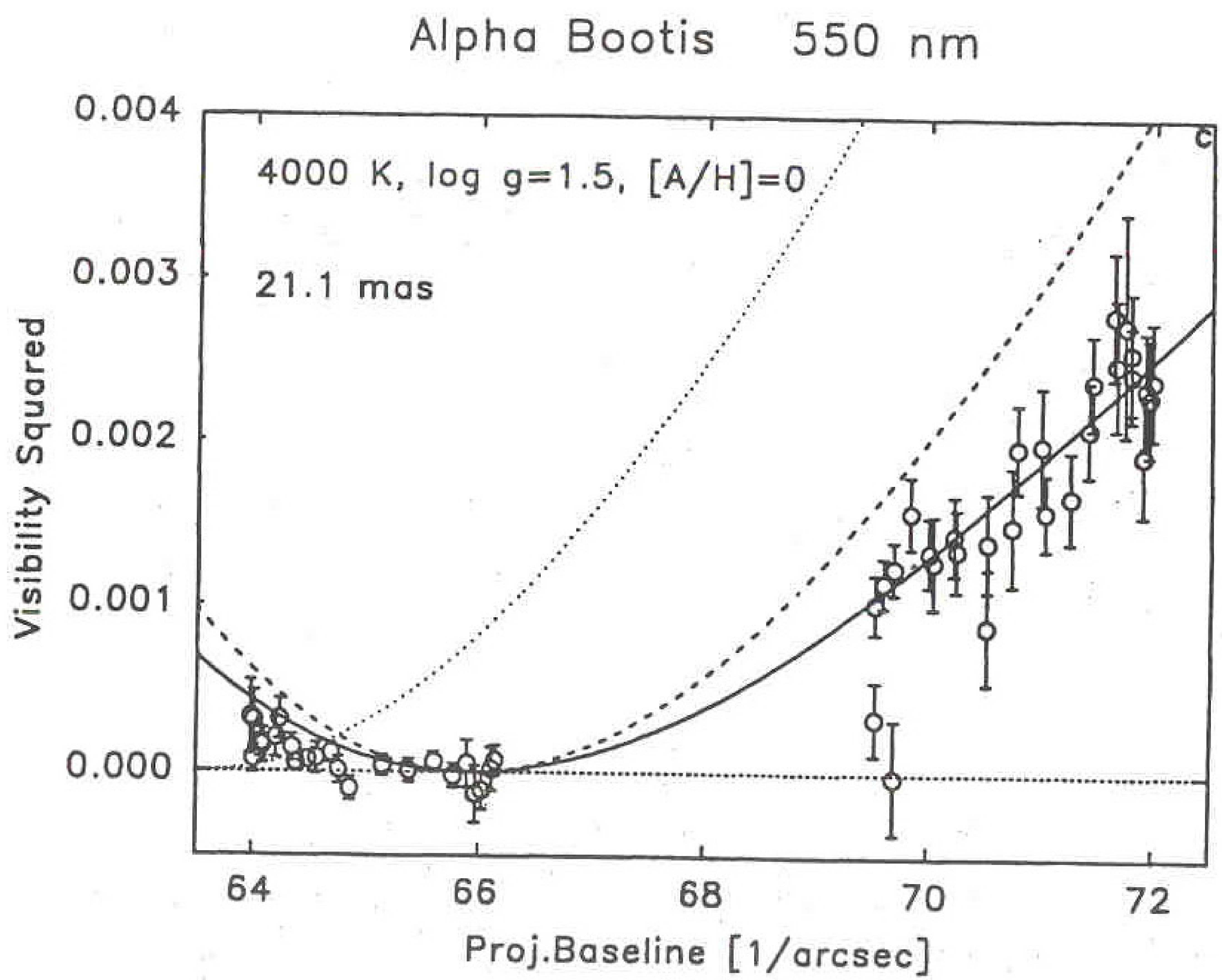
This is the Most Widespread Technique used to Date.

Pro

An Interferometer with a Wide Bandpass is a Good Thing.

Con

It is Difficult to Get More Than a Couple Factors of 2 in Baseline Length. This Limits the Maximum resolution to a few Pixels Across the Source.


Alpha Bootis 550 nm
4000 K, log g=1.5, [A/H]=0
21.1 mas
c
Visibility Squared
0.004
0.003
0.002
0.001
0.000
64
66
68
70
72
Proj.Baseline [1/arcsec]

Alternative 4: Baseline Bootstraping

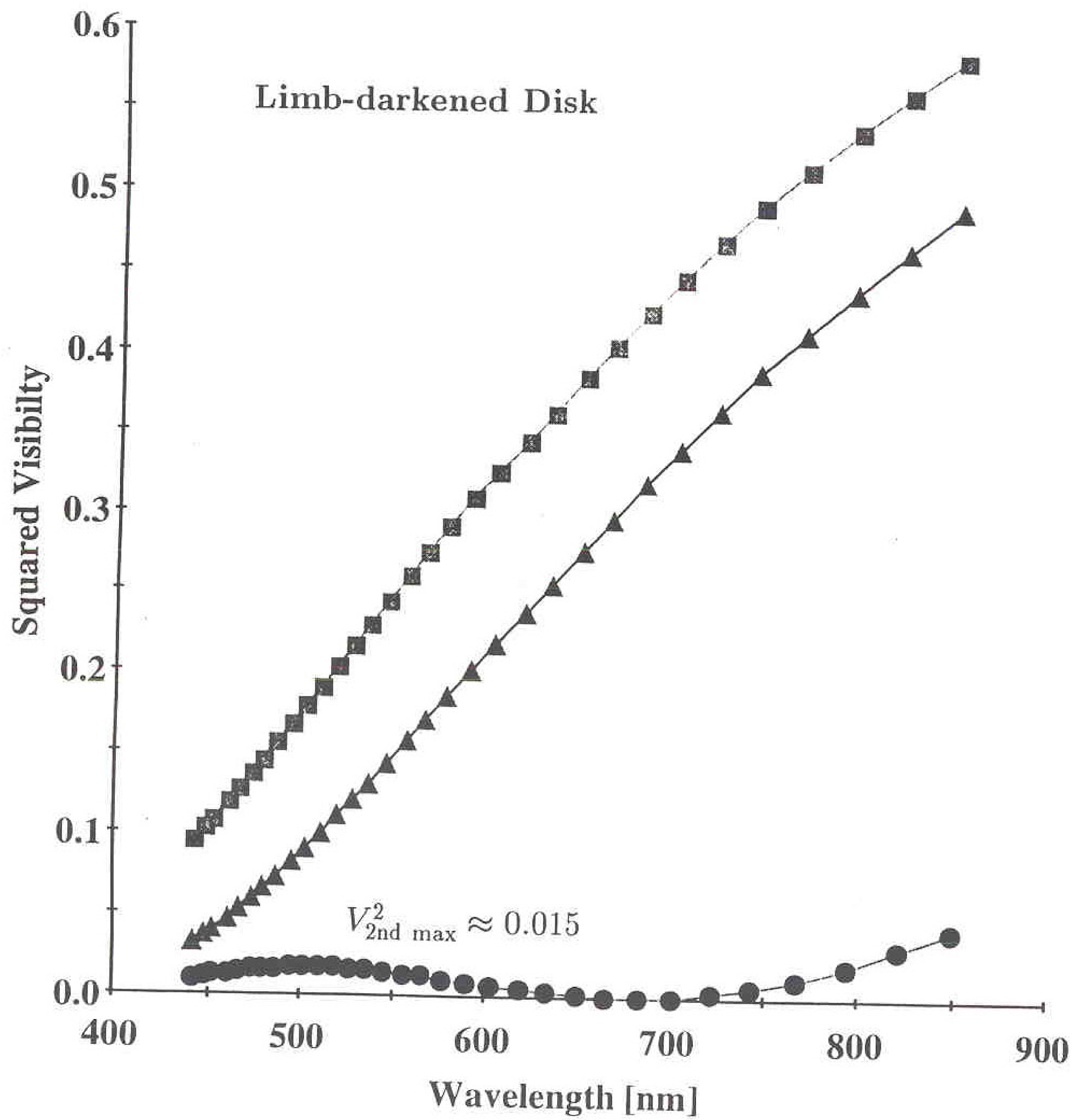
Use Redundant Arrays:

Make a Long Baseline out of Several Short Baselines.

Observe on ALL Baselines at Once.

A.........B.........C.........D.........E

Squared Visibilty



Alternative 5: Guide Star Methods

Observe Two Objects in the same FOV.

Track Fringes on Guide Star.

Passively Observe on Target Star.

pros:

Potentially Very Powerful in the Thermal Infrared.

Should Produce Some Interesting Science in the Near IR.

cons:

Requires Large Telescopes

Amount of Phase Noise on Target Star is a Strong Function of Seeing and Angle Between Target and Guide.

The FOV is Too Small to be Useful at Visible
WAVELENGTHS WITH NATURAL GUIDE STARS

Optimal Design of Interferometric Arrays

Tremendous Amount of Work at Radio Wavelengths

- Random Arrays
- Cornwell Circles
- Reuleaux Triangles
- Non-redundant Y (VLA)

Probably none if it is Applicable at Visible Wavelengths

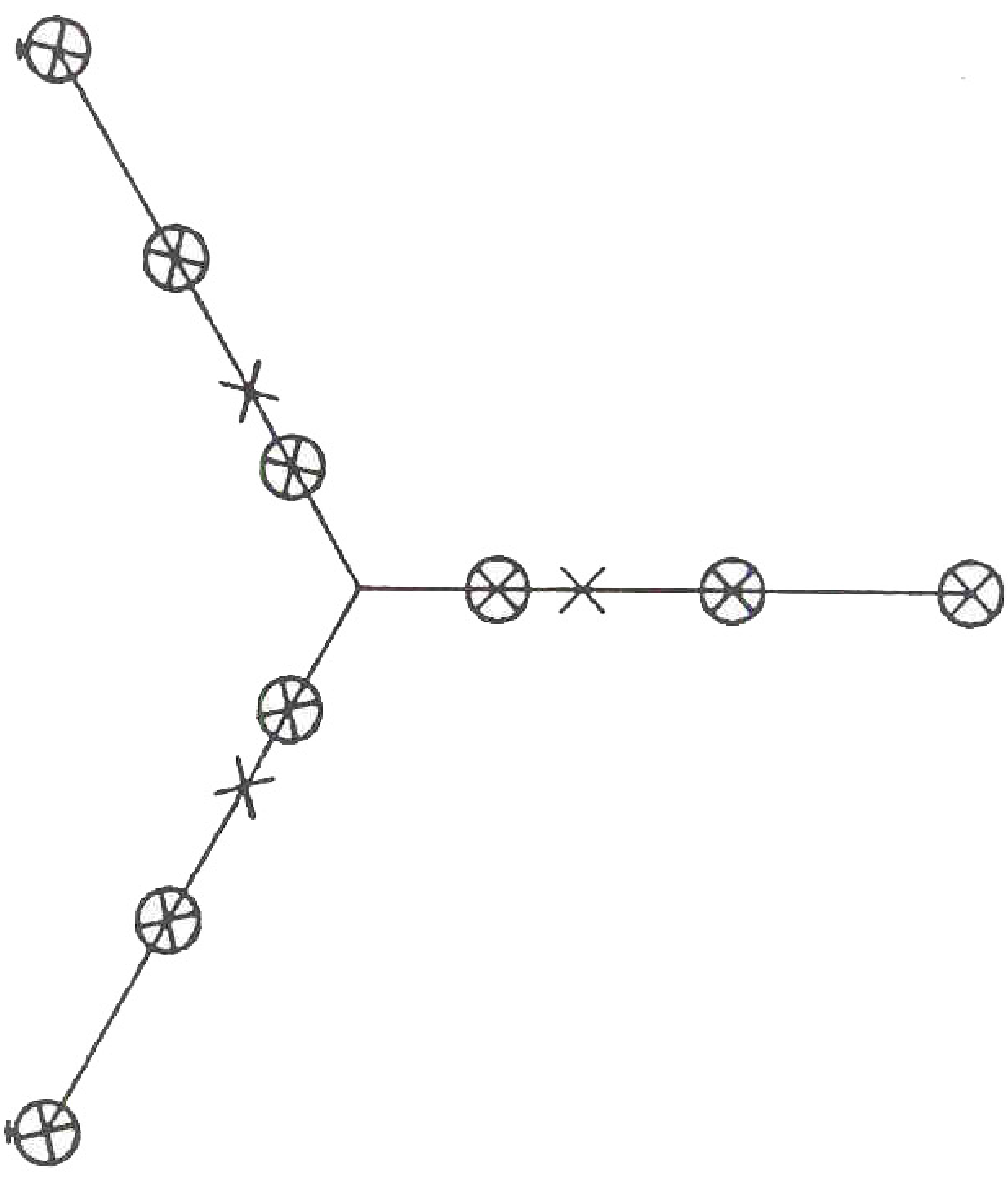
Optimal Usually Means Most Uniform (u,v) Coverage
(but see recent work at MIT)

Optical Interferometric Array Layout for Imaging

Imaging *Requires* Redundant Arrays.
for Baseline Bootstrapping

Optical Interferometry *Requires* Vacuum Feed System.
for Control of Instrumental Seeing

A Partially Redundant Y Seems to be
the *Only* Reasonable Choice



Polarization and Beam Rotation Effects

The Rule of Optics Requires us to be Careful with the Symmetry of the Reflections on Each Arm of the Interferometer.

Beam Rotation: E-vectors Must Line Up

Polarization Dependent Phase Shift: Important
Even if There is no Net Induced Linear Polarization

Mirrors Act like Waveplates.

Beam Combination and Modulation

After Combining the Light, we Need to Know

If a Fringe is Present

Its Amplitude and Phase

The Type of Detection Technique Depends on the Type Beam Combination Technique.

Fringe Detection Schemes

Beam Combination Strategies

Pupil plane: Passive detection

$$\frac{<(A-B)^2>}{<(A+B)^2>}$$

Very Simple

Minimum Number of Detectors

Not Useful with Multiple Baselines
No Phase Information Retained.

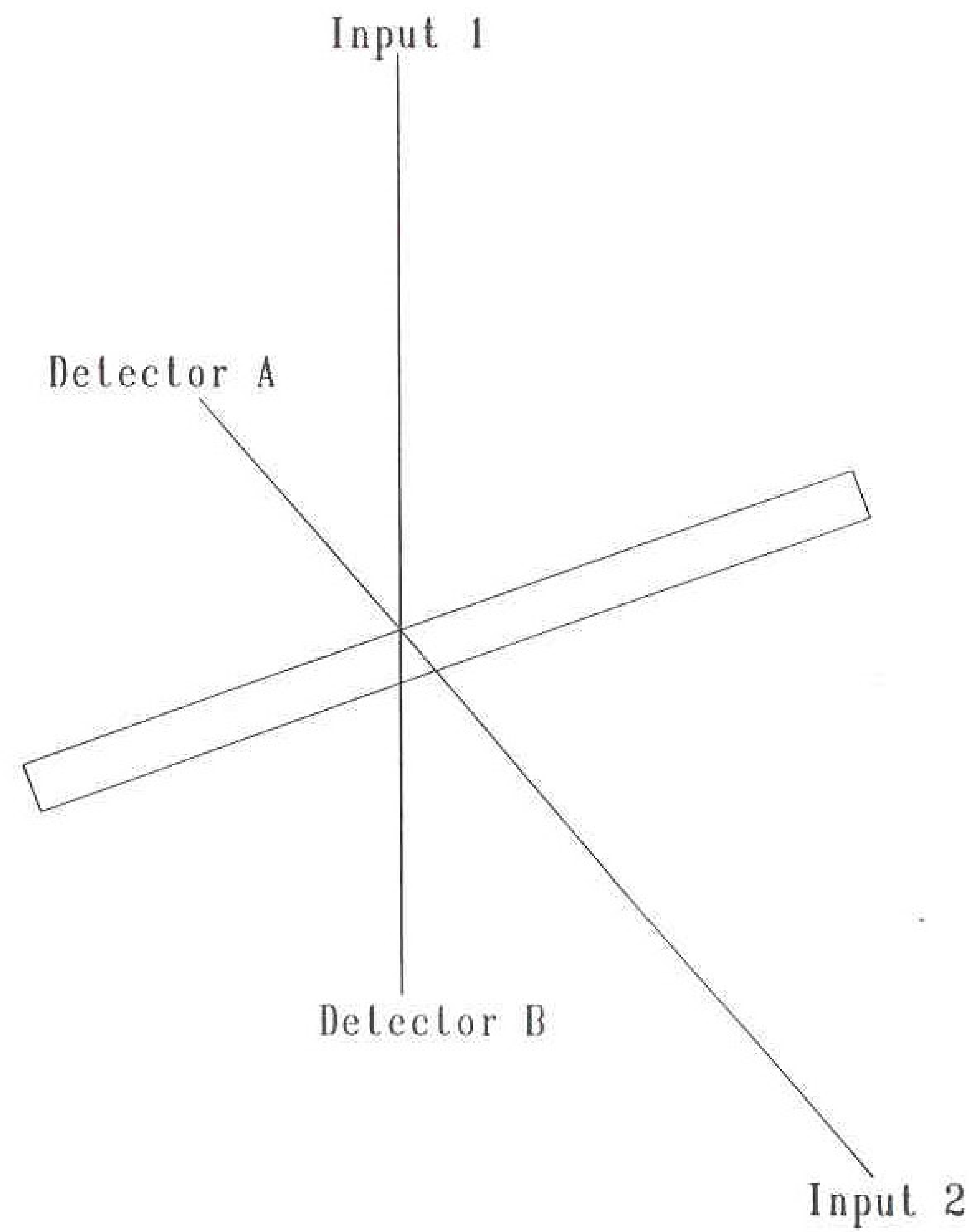
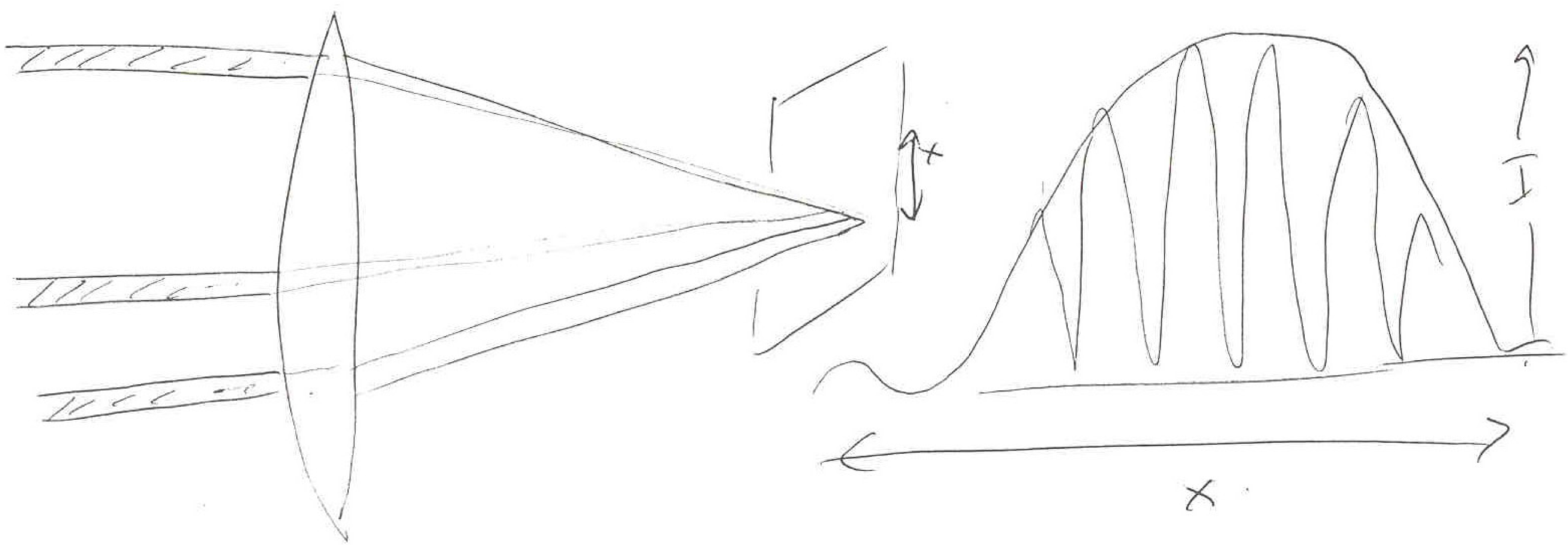


Image plane: Spatial Modulation

All Aperture Masking, I2T, GI2T

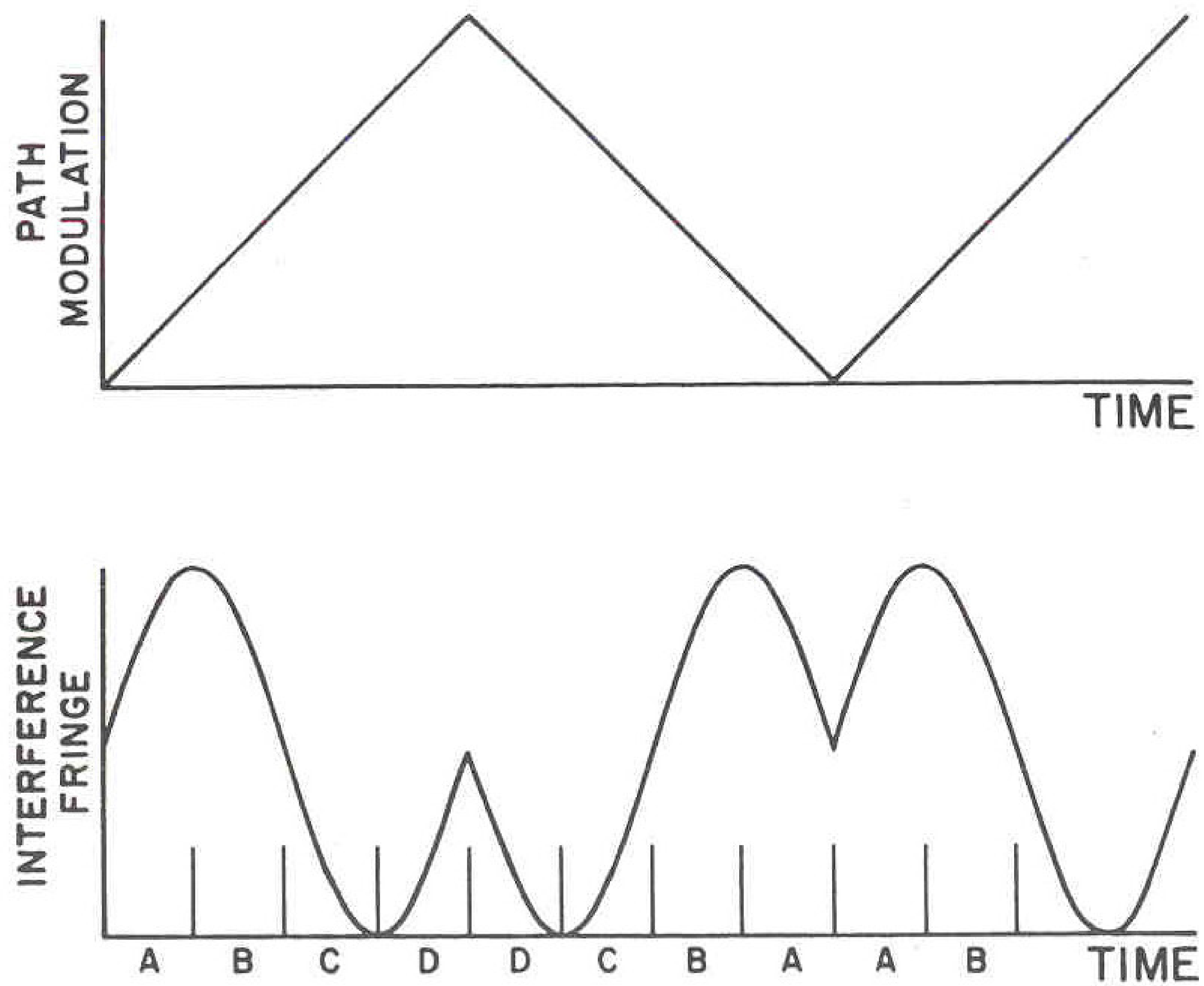
Stuff beams through a single lens
Diffraction pattern of lens gives fringes.



Pupil plane: Time modulation

Modulate Path Length Rapidly Relative to Atmosphere.

Detect Photons Synchronously with the Modulation.


PATH MODULATION
TIME
INTERFERENCE FRINGE
A B C D D C B A A B
TIME

How do we deal with Multiple Baselines?

What is the Best way to Combine Light from Multiple Telescopes?

Measure Data Three Baselines (one Triangle) at a Time.

Pair-wise Combination

One Detector For Each Baseline

All-on-one Combination

Each Detector Sees Light from All Telescopes

Somewhere in Between

Partial-Pairwise Combination

Some Light for Fringe Tracking, the Rest for Science

DEMODULATING MULTIPLE BASELINES

EACH TELESCOPE DELAY IS MODULATED WITH A DIFFERENT AMPLITUDE TRIANGLE

TSCOPE	AMP	B.L	AMP
A	0	AB	1
B	1	AC	4
C	4	AD	6
D	6	BC	3
		BD	5
		CD	2

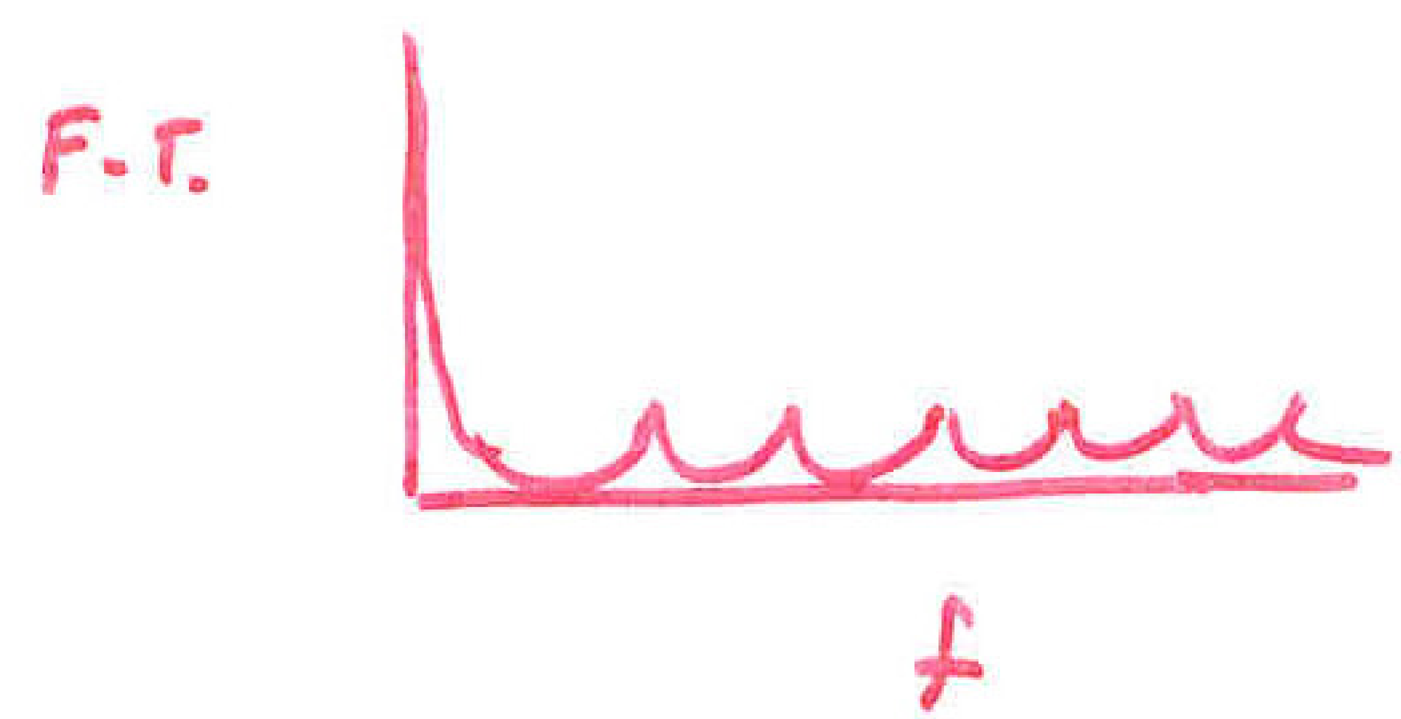
FRINGE FREQUENCY

$$f = \frac{\text{BASELINE AMPLITUDE}(\lambda)}{\text{MODULATION TIME}} = \frac{k}{T_m}$$

THE SIGNAL IS A SUPERPOSITION OF SINES

FOURIER TRANSFORM TIME SERIES

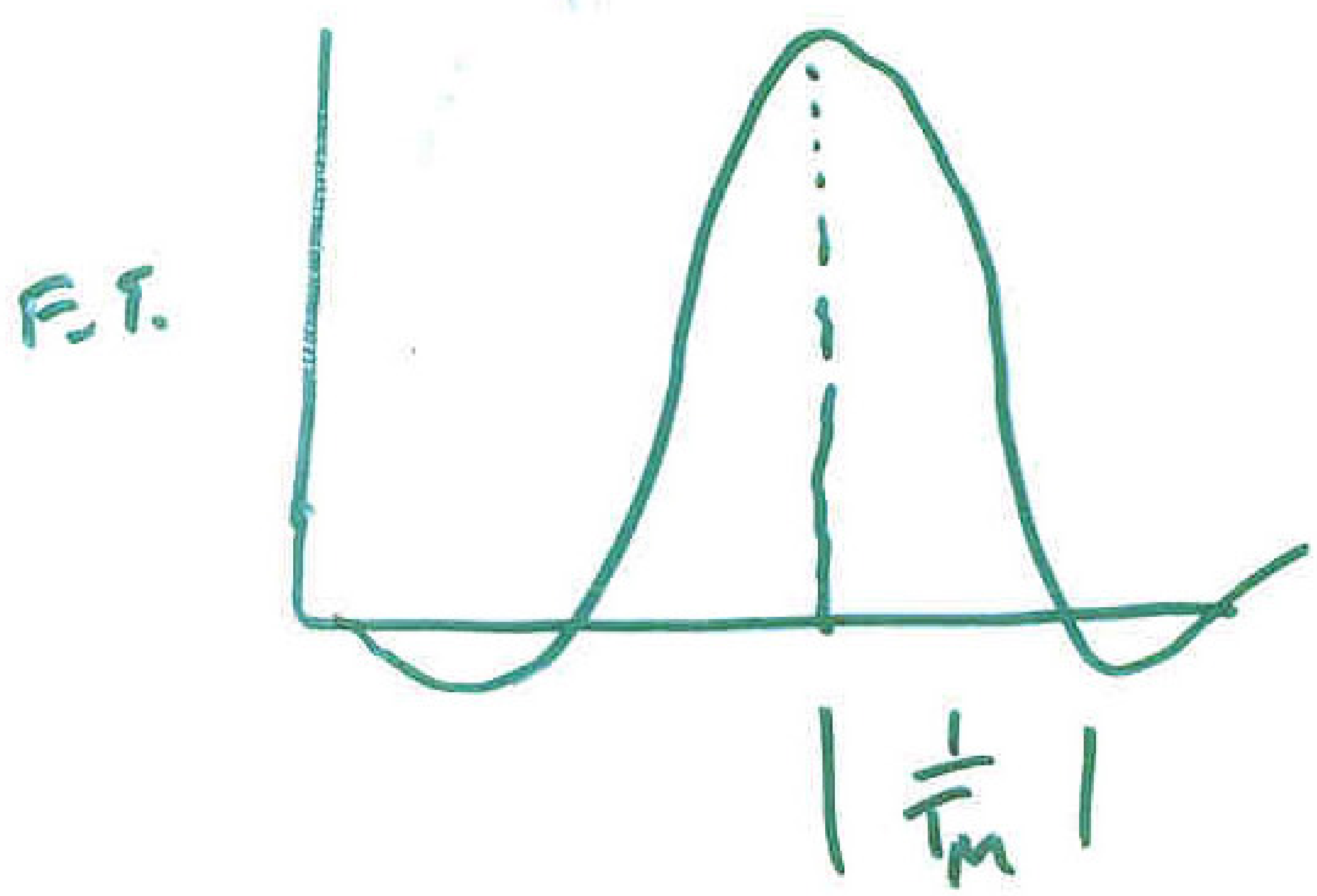
READ OFF AMPLITUDE AND PHASE AT EACH FRINGE FREQUENCY.



BIAS

INCORRECT STROKE BIASES THE FRINGE AMPLITUDE AND PHASE.

F.T. SIGNAL IS SINC FUNCTION, NOT DELTA FUNCTION



INCORRECT STROKE LENGTH RESULTS IN SAMPLING OFF THE PEAK.

ATMOSPHERE SHIFTS FRINGE FREQUENCY

$$\delta f = \frac{1}{2\pi t_0}$$

PHASE BIAS AVERAGES TO ZERO IF PHASE IS RANDOM

CROSSTALK

IF FRINGE FREQUENCIES ARE INTEGRAL MULTIPLES, EACH SIGNAL IS AT A ZERO OF ALL OTHER FREQUENCIES.

- NO CROSSTALK

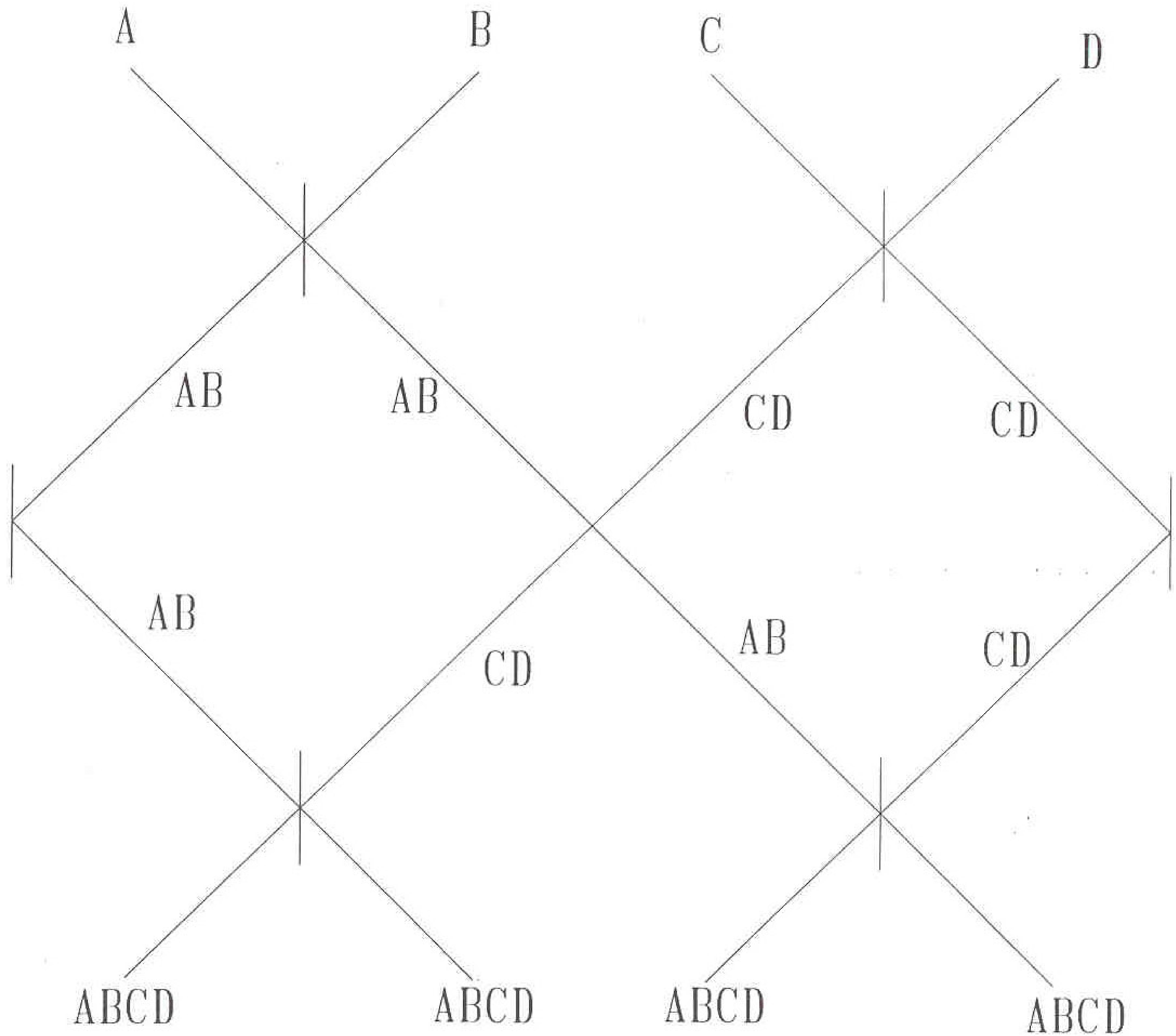
THE ATMOSPHERE CHANGES FRINGE FREQUENCIES

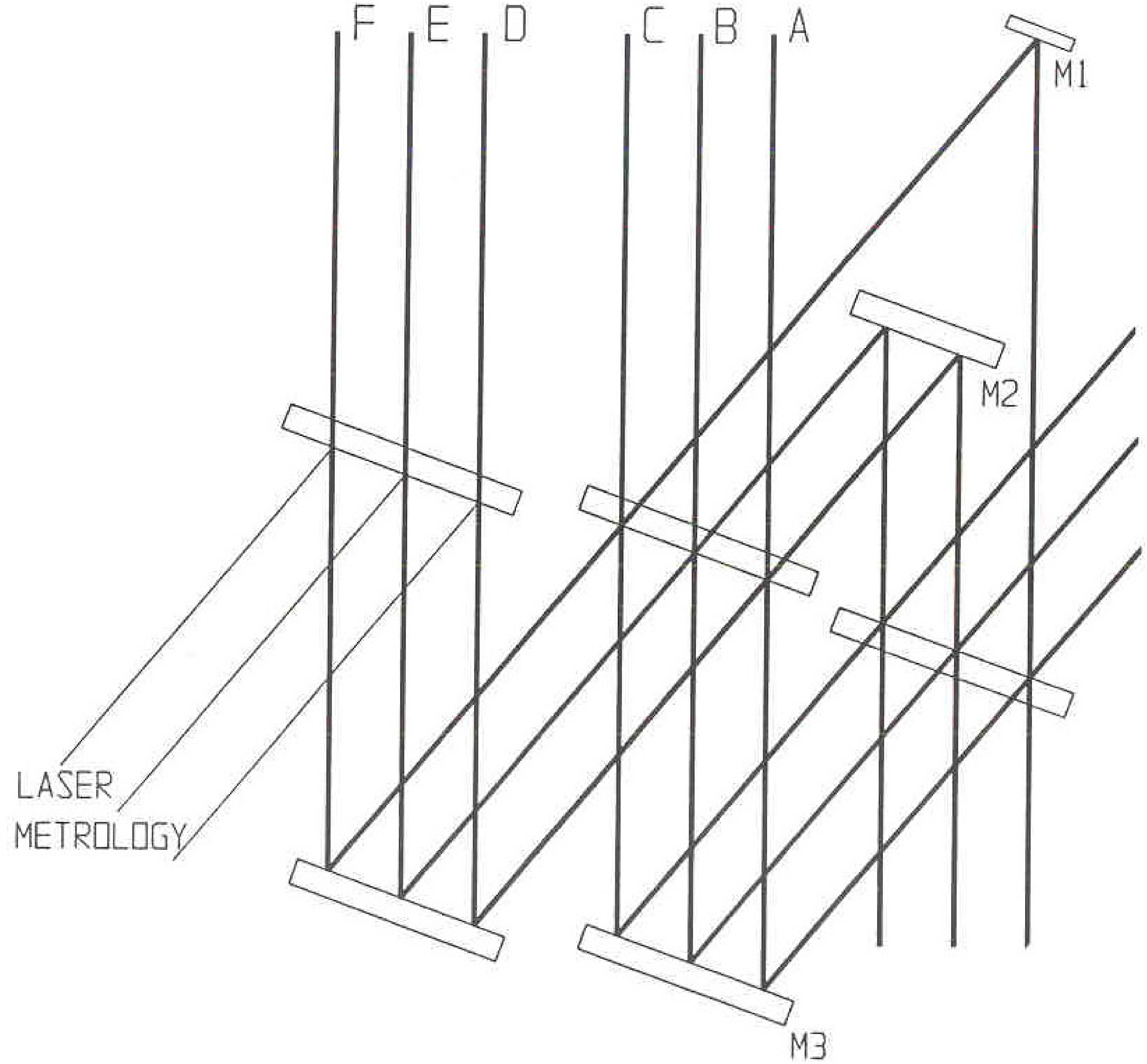
- CROSSTALK <u>LINEAR</u> IN δF

MODULATION FREQUENCY MUST BE INCREASED BY ORDER OF MAGNITUDE OVER SINGLE BASELINE CASE.

ALTERNATIVE

- SPREAD OUT FRINGE FREQUENCIES
  - LONGER STROKE
  - MORE SAMPLES
- APODIZE TO REDUCE SIDE LOBES
  - LOSS of SNR


A
B
C
D
AB
AB
CD
CD
AB
CD
AB
CD
ABCD
ABCD
ABCD
ABCD



F
E
D
C
B
A
M1
M2
M3
LASER
METROLOGY

Comparision of Beam Combination Techniques

Pairwise combination

$N => \frac{N_0 E}{E(E-1)/2}$

$V => V_0$ $\qquad NV^2 = (2N_0)V_0^2(\frac{1}{E-1})$

All-on-One Combination

$N => EN_0$

$V => V_0(\frac{2}{E})$ $\qquad NV^2 = (2N_0)V_0^2(\frac{2}{E})$

NPOI: 6-way Hybrid

$N => 2N_0$

$V => V_0/2$ $\qquad NV^2 = (2N_0)V_0^2(\frac{1}{4})$

CHARA: Partial-pairwise

$N => 2fN_0$

$V => V_0$ $\qquad NV^2 = (2N_0)V_0^2(\frac{f}{2})$

Read noise plays a role at the faint end

The Next Generation of Arrays for Synthesis Imaging Arrays.

WHAT SHOULD WE, AS A COMMUNITY
SUGGEST TO THE DECADE COMMITTEE?

What not to Do

1. Build Another NPOI
   Small Number of Small Telescopes

   Not Sensitive Enough

2. Build Another KI/VLTI
   Small Number of Very Large Telescopes

   These are NOT Imaging Systems

So What do we Do?

Requirements

Very Long Baselines

Note: Shorter Wavelengths Require Longer Baselines!

Flux Limited System Implies
Hotter Objects Observed at Shorter Wavelengths

Increased Surface Brightness wins over Increased Resolution.

Most Interesting Sources are too Faint for Current Instruments.

Implications

Baseline

5 kilometers – 10 pixels across $m_V = 4$ O Star

Clear Aperture

1 to 2 meters with Low Order AO

– to reach $m_V = 10$

Spatial Filtering with SMF at the Telescope

To Allow Calibration of Data

As Many Telescopes as Budget Allows

For Baseline Bootstrap, not Speed or Sensitivity

Bandpass – V to K